

No-Scale μ -Term Hybrid Inflation

Lina Wu^{a,b,1}, Shan Hu^{c,2}, Tianjun Li^{a,b,d,3}

^a*School of Physical Electronics, University of Electronic Science and Technology of China,
Chengdu 610054, P. R. China*

^b*Key Laboratory of Theoretical Physics and Kavli Institute for Theoretical Physics China
(KITPC), Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P.
R. China*

^c*Department of Physics and Electronic Technology, Hubei University, Wuhan 430062, P. R.
China*

^d*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, P.
R. China*

Abstract

To solve the fine-tuning problem in μ -Term Hybrid Inflation, we will realize the supersymmetry scenario with the TeV-scale supersymmetric particles and intermediate-scale gravitino from anomaly mediation, which can be consistent with the WMAP and Planck experiments. Moreover, we for the first time propose the μ -term hybrid inflation in no-scale supergravity. With four Scenarios for the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model, we show that the correct scalar spectral index n_s can be obtained, while the tensor-to-scalar ratio r is predicted to be tiny, about $10^{-10} - 10^{-8}$. Also, the $SU(2)_R \times U(1)_{B-L}$ symmetry breaking scale is around 10^{14} GeV, and all the supersymmetric particles except gravitino are around TeV scale while gravitino mass is around 10^{9-10} GeV. Considering the complete potential terms linear in S , we for the first time show that the tadpole term, which is the key for such kind of inflationary models to be consistent with the observed scalar spectral index, vanishes after inflation. Thus, to obtain the μ term, we need to generate the supersymmetry breaking soft term $A_\kappa^{S\Phi\Phi'} \kappa S\Phi\Phi'$ due to $A_\kappa^{S\Phi\Phi'} = 0$ in no-scale supergravity, where Φ and Φ' are vector-like Higgs fields at high energy. We show that the proper $A_\kappa^{S\Phi\Phi'} \kappa S\Phi\Phi'$ term can be obtained in the M-theory inspired no-scale supergravity. We also point out that $A_\kappa^{S\Phi\Phi'}$ around 700 GeV can be generated via the renormalization group equation running from string scale.

¹E-mail:wulina@std.uestc.edu.cn

²E-mail:hushan@itp.ac.cn

³E-mail:tli@itp.ac.cn

It is well-known that our Universe may experience an accelerated expansion, *i.e.*, inflation [1, 2, 3, 4], at a very early stage of evolution, as suggested by the observed temperature fluctuations in the cosmic microwave background radiation (CMB). From the particle physics point of view, supersymmetry is the most promising extension for the Standard Model (SM). In particular, the scalar masses can be stabilized, and superpotential is non-renormalized. Because gravity is also very important in the early Universe, it seems to us that supergravity theory is a natural framework for inflationary model building [5].

The F-term hybrid inflation in a supersymmetric high energy model with gauge symmetry G has a renormalizable superpotential W and a canonical Kähler potential K [6, 7]. In particular, the Z_2 R -parity in the Supersymmetric SMs (SSMs) is extended to a continuous $U(1)_R$ symmetry, which determines superpotential. With the minimal W and K , the gauge symmetry G is broken down to a subgroup H at the end of inflation. For the supersymmetric high energy model, in general, we can consider either a left-right model with gauge symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, or a Grand Unified Theory (GUT) such as $SU(5)$ model, flipped $SU(5) \times U(1)_X$ model, or Pati-Salam $SU(4)_c \times SU(2)_L \times SU(2)_R$ model [8]. While H can be the SM or SM-like gauge group, etc.

In the original supersymmetric hybrid inflation models, the quantum corrections arising from supersymmetry breaking drive inflation, and the scalar spectral index was predicted to be $n_s = 1 - 1/N \simeq 0.98$ [6], where $N = 60$ denotes the number of e-foldings necessary to resolve the horizon and flatness problems in Big Bang cosmology. Interestingly, with a class of linear supersymmetry breaking soft terms in the inflationary potential [9, 10], such kind of models can be highly consistent with the observed scalar spectral index values of $n_s = 0.96 - 0.97$ from the WMAP [11] and Planck satellite experiments [12] as well. In particular, the corresponding supersymmetry breaking A -term for the linear superpotential term can be around TeV scale [9, 10].

As we know, in the Minimal SSM (MSSM), there exists a well-known μ problem. However, the $\mu H_d H_u$ term is forbidden by $U(1)_R$ symmetry, where H_u and H_u are one pair of Higgs fields in the SSMs. With the linear supersymmetry breaking soft term after inflation, the inflaton field S acquires a Vacuum Expectation Value (VEV). Thus, the μ problem can be solved if there exists a superpotential term $\lambda S H_d H_u$, as proposed by Dvali, Lazarides and Shafi (DLS) [13]. Assuming the minimal K , the magnitude of μ is typically around the gravitino mass m_G [13]. Recently, such scenario has been studied in details [14]. With the reheating and cosmological gravitino constraints, it was found that a consistent inflationary scenario gives rather concrete predictions regarding supersymmetric dark matter and Large Hadron Collider (LHC) phenomenology. Especially, the gravitino must be sufficiently heavy ($m_G \gtrsim 5 \times 10^7$

GeV) so that it decays before the freeze out of the lightest supersymmetric particle (LSP) neutralino, which is the dark matter candidate. Moreover, the wino with mass $\simeq 2$ TeV becomes a compelling dark matter candidate. And the supersymmetry breaking scalar mass M_0 is expected to be of the same order as m_G or larger, which can reproduce a SM-like Higgs boson mass $\simeq 125$ GeV for suitable $\tan\beta$ values, where $\tan\beta$ is the ratio of the VEVs for H_u and H_d . Depending on the underlying gauge symmetry G associated with inflationary scenario, the observed baryon asymmetry in the Universe can be explained via leptogenesis [15, 16]. The compelling examples of G , in which the DLS mechanism can be successfully merged with inflation, contain $U(1)_{B-L}$, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, and flipped $SU(5) \times U(1)_X$. The other examples of G are $SU(5)$ and $SU(4)_C \times SU(2)_L \times SU(2)_R$ [8], but there may exist monopole problem.

In short, in the recent study [14], to solve the gravitino problem in the μ -term hybrid inflation, Okada and Shafi showed that the sfermions, Higgsinos, and gravitino are heavy around 10^7 GeV while gauginos are light around TeV, which are similar to the split supersymmetry [17, 18]⁴. Thus, the supersymmetry solution to gauge hierarchy problem is at least partly gone, *i.e.*, there exists big fine-tuning around 10^{-10} . On the other hand, even if the corresponding supersymmetry breaking A -term for the linear superpotential term is around TeV scale [9, 10], we can still obtain the observed scalar spectral index values of $n_s = 0.96 - 0.97$ from the WMAP [11] and Planck satellite experiments [12]. Therefore, to solve this problem, we do need the supersymmetry scenario, which can have the TeV-scale supersymmetric particles (sparticles) in the SSMs while intermediate-scale heavy gravitino. The well-known example is no-scale supergravity [21] or its generalization. In this paper, we shall realize such supersymmetry scenario via anomaly mediation [18]. In addition, we for the first time propose the μ -term hybrid inflation in no-scale supergravity⁵. We discuss it in details, and find some interesting results different from the previous study on the μ -term hybrid inflation.

First, with anomaly mediation, we will derive the supersymmetry scenario, where the sparticles are light while gravitino is heavy [18]. We consider the Kähler potential and superpotential as follows

$$K = -3M_{Pl}^2 (z + \bar{z} + \epsilon f(z, \bar{z})) \bar{X}X + \sum_Y \bar{Y}Y, \quad (1)$$

$$W = X^3 W_0 + S (\kappa X^2 M^2 - \kappa \Phi' \Phi + \lambda H_d H_u), \quad (2)$$

⁴The supersymmetric hybrid inflation model with a no-scale form of the Kahler potential, which is based on a Heisenberg symmetry, has been studied before to solve the η problem [19, 20].

⁵The gravitino mass can be around the TeV scale if there exists extra D-term contribution [22].

where M_{Pl} is the reduced Planck scale, z and X are respectively a hidden sector superfield and a compensator multiplet ($X = 1 + F_X$), Y denotes all the other superfields, ϵ is a small parameter, W_0 is a constant superpotential, and Φ' and Φ are the Higgs fields which breaks the high-scale gauge symmetry in the F-term hybrid inflation [6, 7]. Similar to the no-scale supergravity, the scalar potential vanishes in the limit $\epsilon \rightarrow 0$. Considering the equations of motion for the auxiliary fields, we obtain

$$F_X \simeq -\frac{W_0^\dagger}{M_{Pl}^2} \epsilon f_{\bar{z}z} = -\epsilon m_G f_{\bar{z}z}, \quad F_z \simeq \frac{W_0^\dagger}{M_{Pl}^2} = m_G, \quad (3)$$

for small ϵ . Here, we define $f_{\bar{z}z} \equiv \partial^2 f(z, \bar{z}) / \partial \bar{z} \partial z$, and m_G is gravitino mass. So the scalar potential becomes

$$V = -3F_X W_0 \simeq 3 \frac{|W_0|^2}{M_{Pl}^2} \epsilon f_{\bar{z}z} = 3\epsilon m_G^2 M_{Pl}^2 f_{\bar{z}z}. \quad (4)$$

For example, assuming $f_{\bar{z}z} = (|z|^2 - 1/4)^2 - 1$, we get the minimum for the scalar potential at $\langle z \rangle = 1/2$

$$V_{\min} \simeq -3\epsilon m_G^2 M_{Pl}^2, \quad (5)$$

which is an AdS vacuum. Thus, we have $F_X \simeq \epsilon m_G \ll m_G$. Because the supersymmetry breaking soft terms in the SSMs are proportional to F_X via anomaly mediation, we obtain the supersymmetry breaking scenario which has TeV-scale sparticles and intermediate-scale gravitino. In particular, the supersymmetry breaking linear term for S is given by

$$V = -4\kappa F_X M^2 S + \text{H.C} \simeq -4\kappa \epsilon m_G M^2 S + \text{H.C}. \quad (6)$$

From the numerical studies in Refs. [9, 10], we can still obtain the observed scalar spectral index values of $n_s = 0.96 - 0.97$ from the WMAP [11] and Planck satellite experiments [12] as well. By the way, the AdS vacuum given by Eq. (5) can be lifted to the Minkowski vacuum by considering the F -term and D -term contributions in the anomalous $U(1)$ theory inspired from string models [18].

In the following, we shall embed the previous μ -term hybrid inflation scenario into no-scale supergravity framework, *i.e.*, we propose the μ -term hybrid inflation in no-scale supergravity where μ term is generated via the VEV of inflaton field after inflation. We introduce a conjugate pair of vector-like Higgs fields Φ and Φ' , which breaks G down to the SM or SM-like gauge symmetry. Considering four Scenarios for the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model, we show that the correct scalar spectral index n_s can be obtained, while the tensor-to-scalar ratio r is predicted to be tiny, about $10^{-10} - 10^{-8}$. Also, the $SU(2)_R \times U(1)_{B-L}$ symmetry

breaking scale is around 10^{14} GeV, and all the supersymmetric particles except gravitino are around TeV scale while gravitino mass is around 10^{9-10} GeV. We present the complete potential terms that are linear in S , and for the first time we show that the tadpole term, which is the key for such kind of inflationary models to be consistent with the observed scalar spectral index, vanishes after inflation or say gauge symmetry G breaking. Thus, to reproduce the μ term, we need to generate the supersymmetry breaking soft term $A_\kappa^{S\Phi\Phi'} \kappa S \Phi \Phi'$ since we have $A_\kappa^{S\Phi\Phi'} = 0$ in no-scale supergravity. We show that the supersymmetry breaking soft term $A_\kappa^{S\Phi\Phi'} \kappa S \Phi \Phi'$ can be generated properly in the M-theory inspired no-scale supergravity which has no-scale supergravity at the leading or lowest order [23, 24, 25, 26, 27]. We also point out that the $A_\kappa^{S\Phi\Phi'} \kappa S \Phi \Phi'$ term with $A_\kappa^{S\Phi\Phi'}$ around 700 GeV can be obtained via the renormalization group equation (RGE) running from string scale [28, 29, 30, 31]. Therefore, we solve the fine-tuning problem in the previous μ -term hybrid inflation, and propose the no-scale μ -term hybrid inflation models where the sparticles in the SSMs are around TeV scale while gravitino is around 10^{9-10} GeV.

Let us present our model in the following. The Kähler potential is

$$K = \bar{S}S - 3\ln(T + \bar{T} - 2\bar{C}_i C_i) , \quad (7)$$

where T is a modulus, and C_i are matter/Higgs fields in the supersymmetric SMs which include Φ , Φ' , H_u , and H_d . To simplify the discussions, we will assume $\langle T \rangle = 1/2$ in the following study.

Assuming S and superpotential have charge 2 while Φ , Φ' , H_u and H_d are neutral under the $U(1)_R$ R-symmetry, we obtain the $U(1)_R$ invariant inflaton superpotential [13]

$$W = S (\kappa \Phi' \Phi - \kappa M^2 + \lambda H_d H_u) . \quad (8)$$

To realize the correct symmetry breaking pattern after inflation, we require $\lambda > \kappa$ [13]. In particular, the $\mu H_d H_u$ term is forbidden by the $U(1)_R$ R-symmetry, and then such term can be generated only after $U(1)_R$ R-symmetry is broken down to a Z_2 symmetry, for example, by the VEV of S .

Assuming that the F-term of T breaks supersymmetry, we obtain the following scalar potential which is linear in S

$$V \supset m_G S (\kappa \Phi' \Phi - \kappa M^2 + \lambda H_d H_u) + \text{H.C.} . \quad (9)$$

As a side remark, for Polonyi model, we will have an extra (-2) factor in the above tadpole term due to the $-3|W|^2$ contribution. During inflation, we have $\langle \Phi \rangle = \langle \Phi' \rangle = 0$, as well as a tadpole term for S

$$V \supset -\kappa m_G M^2 S + \text{H.C.} . \quad (10)$$

After inflation (or say after gauge symmetry G breaking) and neglecting the VEVs of H_u and H_d , we have $\langle \Phi \rangle = \langle \Phi' \rangle = M$, and then the above tadpole term vanishes. To obtain the μ term which is forbidden by $U(1)_R$ symmetry, we need to generate the tadpole term of S , which will be discussed below.

With the supersymmetry breaking soft mass term as well as the radiative and supergravity corrections, we obtain the inflationary potential as follows

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + m^4 \left(1 + \alpha \ln \left[\frac{\phi}{\phi_0} \right] + \frac{3\phi^2}{2M_{\text{Pl}}^2} + \frac{7\phi^4}{8M_{\text{Pl}}^4} \right) - \sqrt{2}m_G m^2 \phi, \quad (11)$$

where $m = \sqrt{\kappa}M$, ϕ is the real part of S , m_ϕ is the supersymmetry breaking soft mass, M_{Pl} is the reduced Planck scale, the renormalization scale (Q) is chosen to be equal to the initial inflaton VEV ϕ_0 , and the coefficient $\alpha \ll 1$ is given by

$$\alpha = \frac{1}{4\pi^2} \left(\lambda^2 + \frac{N_\Phi}{2} \kappa^2 \right). \quad (12)$$

In particular, the negative sign of the linear term is essential to generate the correct value for the spectral index. Without this linear term, the scalar spectral index n_s is predicted to lie close to 0.98, as shown in Ref. [6]. Moreover, both ϕ^2 and ϕ^4 terms arise from the leading supergravity contribution, the quadratic supersymmetry breaking soft term can be ignored relative to the linear term in Eq. (11) [9, 10], and the imaginary part of S is assumed to stay constant during inflation [For a more complete discussion of this last point, see Ref. [10].]. Thus, the inflaton potential can be simplified to

$$V(\phi) = m^4 \left(1 + \alpha \ln \left[\frac{\phi}{\phi_0} \right] + \frac{3\phi^2}{2M_{\text{Pl}}^2} + \frac{7\phi^4}{8M_{\text{Pl}}^4} \right) - \sqrt{2}m_G m^2 \phi, \quad (13)$$

In the following discussions, to be concrete, we consider the left-right model with gauge symmetry $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Because Φ and Φ' respectively have quantum numbers $(\mathbf{1}, \mathbf{1}, \mathbf{2}, \mathbf{1}/2)$ and $(\mathbf{1}, \mathbf{1}, \mathbf{2}, -\mathbf{1}/2)$, we get $N_\Phi = 2$. For simplicity, we set $\gamma \equiv \lambda/\kappa = 2$, and then have $\tilde{\gamma} \equiv \sqrt{\gamma^2 + N_\Phi/2} = \sqrt{5}$. Moreover, it seems to us that the ϕ^4 term can be neglected as well. Therefore, we will study the following four scenarios where the power spectrum $\Delta_R^2 = 2.20 \times 10^{-9}$ from the Planck 2015 results [12] has been explained simultaneously:

Scenario I. The potential in Eq. (11) with $m_\phi \simeq m_G$.

To obtain $0.955 \leq n_s \leq 0.977$ within about 1σ range of the Planck 2015 results [12] and the e-folding number $27 \leq N \leq 72$, we present the numerical values of M and m_G for the viable points in Fig. (1), which are normalized by the reduced Planck scale $M_{\text{Pl}} =$

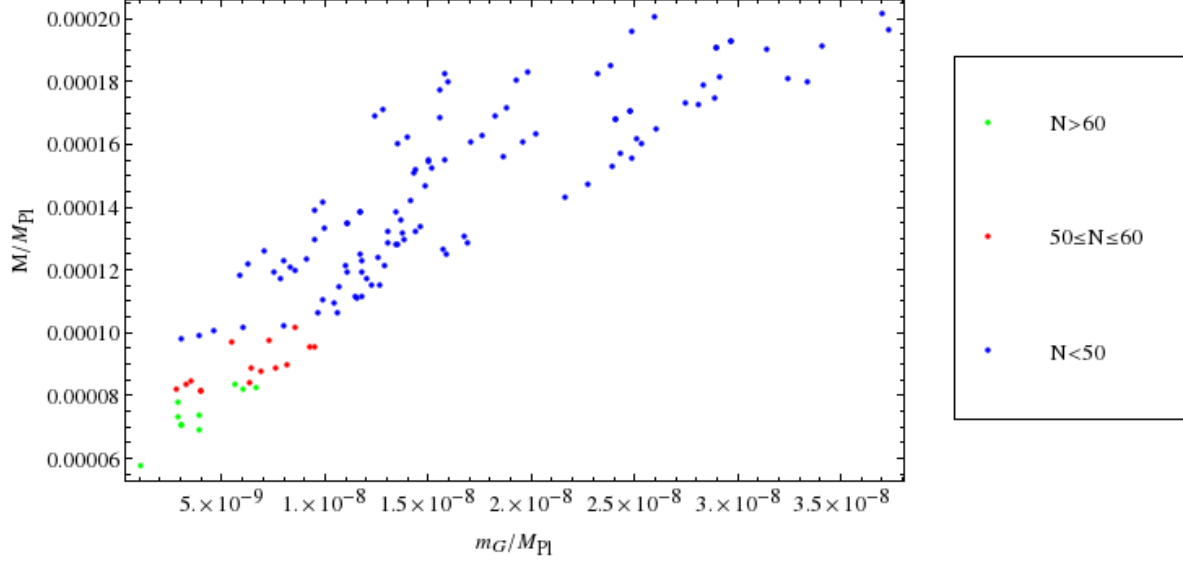


Figure 1: The allowed numerical values for M and m_G to get $0.955 \leq n_s \leq 0.977$ and $27 \leq N \leq 72$ for the potential in Eq. (11) with $m_\phi \simeq m_G$. Here, we have $0.358747 \leq \kappa \leq 1.02244$.

2.43×10^{18} GeV. The corresponding range of κ is $0.358747 \leq \kappa \leq 1.02244$. According to the figure, we can see with the increasing of N , both M and m_G decrease. The best fit point with the Planck results has $n_s = 0.964677$, $r = 1.32516 \times 10^{-9}$, and $N = 55$, which can be obtained by choosing $\kappa = 0.46682$, $M = 1.19883 \times 10^{-4} M_{Pl} \approx 2.913 \times 10^{14}$ GeV, and $m_G = 2.8227 \times 10^{-9} M_{Pl} \approx 6.859 \times 10^9$ GeV. Moreover, the minimal value of M locates at $M = 7.44428 \times 10^{-5} M_{Pl} \approx 1.80896 \times 10^{14}$ GeV with the corresponding $\kappa = 0.855067$ and $m_G = 3.96719 \times 10^{-9} M_{Pl} \approx 9.64027 \times 10^9$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.966343$, $r = 5.94759 \times 10^{-10}$, and $N = 71$, respectively. Also, the minimal value of m_G locates at $m_G = 1.09362 \times 10^{-9} M_{Pl} \approx 2.6575 \times 10^9$ GeV with the corresponding $\kappa = 0.371718$ and $M = 9.42889 \times 10^{-5} M_{Pl} \approx 2.29122 \times 10^{14}$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.958972$, $r = 3.2656 \times 10^{-10}$, and $N = 66$, respectively.

Scenario II. The potential in Eq. (11) with $m_\phi \simeq m_G$ and without the ϕ^4 term.

To obtain $0.955 \leq n_s \leq 0.977$ within about 1σ range of the Planck 2015 results and the e-folding number $27 \leq N \leq 72$, we present the numerical values of M and m_G for the viable points in Fig. (2). The corresponding range of κ is $0.554916 \leq \kappa \leq 1.03625$. The best fit point with the Planck results has $n_s = 0.964383$, $r = 4.99194 \times 10^{-8}$, and $N = 54$, which

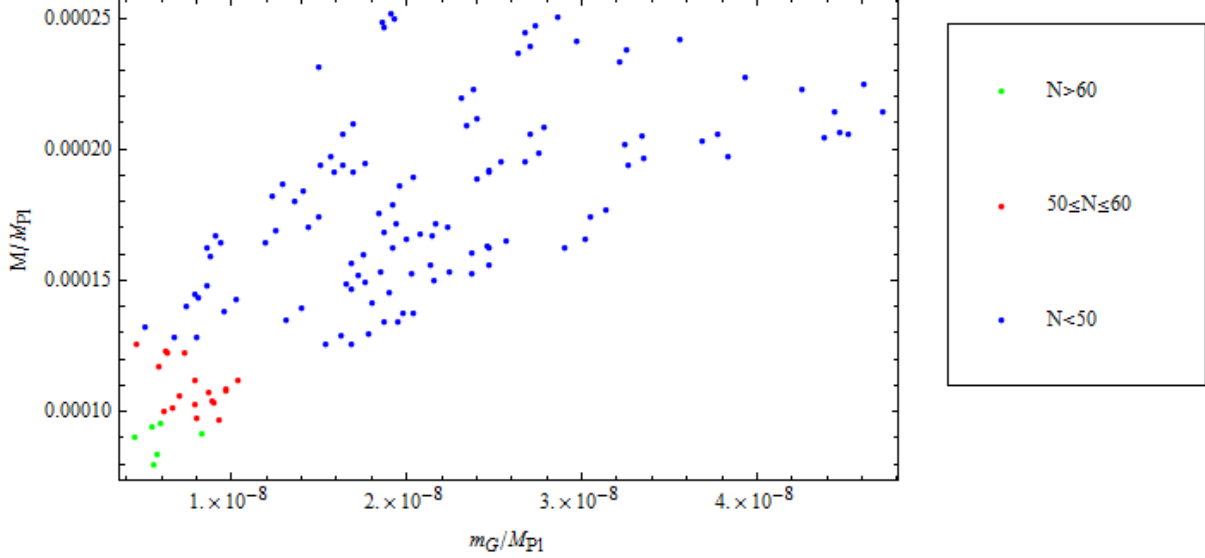


Figure 2: The allowed numerical values for M and m_G to get $0.955 \leq n_s \leq 0.977$ and $27 \leq N \leq 72$ for the potential in Eq. (11) with $m_\phi \simeq m_G$ and without the ϕ^4 term. Here, we have $0.554916 \leq \kappa \leq 1.03625$.

can be obtained by taking $\kappa = 0.694001$, $M = 2.46883 \times 10^{-4} M_{Pl} \approx 5.999 \times 10^{14}$ GeV, and $m_G = 2.73085 \times 10^{-8} M_{Pl} \approx 6.636 \times 10^{10}$ GeV. In addition, the minimal value of M locates at $M = 7.95428 \times 10^{-5} M_{Pl} \approx 1.93289 \times 10^{14}$ GeV with the corresponding $\kappa = 0.94457$ and $m_G = 5.59342 \times 10^{-9} M_{Pl} \approx 1.3592 \times 10^{10}$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.962104$, $r = 9.10999 \times 10^{-10}$, and $N = 67$, respectively. Also, the minimal value of m_G locates at $m_G = 4.52267 \times 10^{-9} M_{Pl} \approx 1.09901 \times 10^{10}$ GeV with the corresponding $\kappa = 0.764382$ and $M = 9.05332 \times 10^{-5} M_{Pl} \approx 2.19996 \times 10^{14}$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.959513$, $r = 1.0716 \times 10^{-9}$, and $N = 64$, respectively.

Scenario III. The potential in Eq. (13).

To obtain $0.955 \leq n_s \leq 0.977$ within about 1σ range of the Planck 2015 results and the e-folding number $27 \leq N \leq 72$, we present the numerical values of M and m_G for the viable points in Fig. (3). The corresponding range of κ is $0.643221 \leq \kappa \leq 0.799225$. The best fit point with the Planck results has $n_s = 0.965618$, $r = 3.52383 \times 10^{-9}$, and $N = 53$, which can be obtained by choosing $\kappa = 0.76438$, $M = 1.2187 \times 10^{-4} M_{Pl} \approx 2.96139 \times 10^{14}$ GeV, and $m_G = 7.66695 \times 10^{-9} M_{Pl} \approx 1.86307 \times 10^{10}$ GeV. Moreover, the minimal value of M locates at $M = 8.20741 \times 10^{-5} M_{Pl} \approx 1.9944 \times 10^{14}$ GeV with the corresponding $\kappa = 0.698536$ and

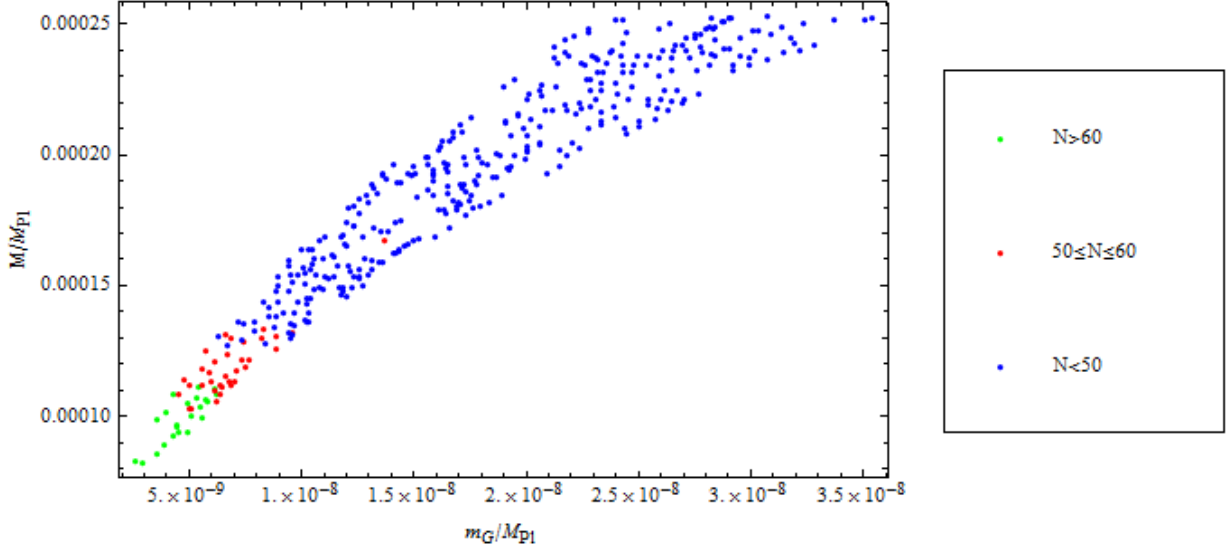


Figure 3: The allowed numerical values for M and m_G to get $0.955 \leq n_s \leq 0.977$ and $27 \leq N \leq 72$ for the potential in Eq. (13). Here, we have $0.643221 \leq \kappa \leq 0.799225$.

$m_G = 2.89804 \times 10^{-9} M_{Pl} \approx 7.04225 \times 10^9$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.955277$, $r = 6.17585 \times 10^{-10}$, and $N = 70$, respectively. Also, the minimal value of m_G locates at $m_G = 2.56278 \times 10^{-9} M_{Pl} \approx 6.22754 \times 10^9$ GeV with the corresponding $\kappa = 0.654176$ and $M = 8.24695 \times 10^{-5} M_{Pl} \approx 2.00401 \times 10^{14}$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.958115$, $r = 5.58929 \times 10^{-10}$, and $N = 71$, respectively.

Scenario IV. The potential in Eq. (13) without the ϕ^4 term.

To obtain $0.955 \leq n_s \leq 0.977$ within about 1σ range of the Planck 2015 results and the e-folding number $27 \leq N \leq 72$, we present the numerical values of M and m_G for the viable points in Fig. (3). The corresponding range of κ is $0.664356 \leq \kappa \leq 0.948324$. The best fit point with the Planck results has $n_s = 0.966235$, $r = 5.4042 \times 10^{-9}$, and $N = 52$, which can be obtained by taking $\kappa = 0.79576$, $M = 1.33317 \times 10^{-4} M_{Pl} \approx 3.23961 \times 10^{14}$ GeV, and $m_G = 9.81092 \times 10^{-9} M_{Pl} \approx 2.38405 \times 10^{10}$ GeV. In addition, the minimal value of M locates at $M = 1.16234 \times 10^{-4} M_{Pl} \approx 2.8245 \times 10^{14}$ GeV with the corresponding $\kappa = 0.917431$ and $m_G = 9.91267 \times 10^{-9} M_{Pl} \approx 2.40878 \times 10^{10}$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.976999$, $r = 3.96363 \times 10^{-9}$, and $N = 62$, respectively. Also, the minimal value of m_G locates at $m_G = 8.71055 \times 10^{-9} M_{Pl} \approx 2.11666 \times 10^{10}$ GeV

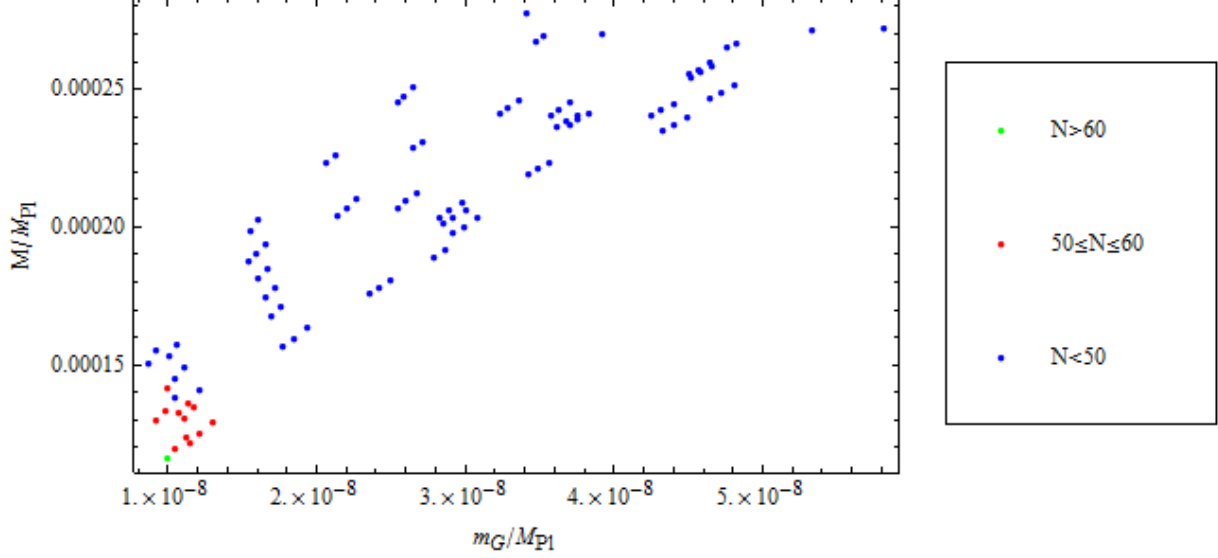


Figure 4: The allowed numerical values for M and m_G to get $0.955 \leq n_s \leq 0.977$ and $27 \leq N \leq 72$ for the potential in Eq. (13) without the ϕ^4 term. Here, we have $0.664356 \leq \kappa \leq 0.948324$.

with the corresponding $\kappa = 0.664356$ and $M = 1.50466 \times 10^{-4} M_{Pl} \approx 3.65632 \times 10^{14}$ GeV. The corresponding inflationary observables and number of e-folding are $n_s = 0.970739$, $r = 6.36454 \times 10^{-9}$, and $N = 48$, respectively.

In short, from the above numerical studies, we find that the observed scalar spectral index n_s can be realized, but the tensor-to-scalar ratio r is predicted to be tiny, about $10^{-10} - 10^{-8}$. Also, the $SU(2)_R \times U(1)_{B-L}$ symmetry breaking scale is around 10^{14} GeV, and the gravitino mass is around 10^{9-10} GeV. Thus, we do need the no-scale supergravity to realize the light sparticle spectrum.

Because gravitino is heavy and then unstable, we encounter the cosmological gravitino problem [32], which originates from the gravitino lifetime

$$\tau_G \simeq 10^4 \text{ sec} \times \left(\frac{1 \text{ TeV}}{m_G} \right)^3. \quad (14)$$

To avoid the constraint on the neutralino abundance from gravitino decay, we assume that the LSP neutralino is still in thermal equilibrium when gravitino decays. So the LSP neutralino abundance is not related to the gravitino yield. Using a typical value of the ratio $x_F \equiv m_{\tilde{\chi}^0}/T_F \simeq 20$, where T_F is the freeze out temperature of the LSP neutralino, this occurs for the gravitino lifetime

$$\tau_G \lesssim 4 \times 10^{-10} \left(\frac{1 \text{ TeV}}{m_{\tilde{\chi}^0}} \right)^2. \quad (15)$$

Combining this with Eq.(14), we find

$$m_G \gtrsim 4.6 \times 10^7 \text{ GeV} \left(\frac{m_{\tilde{\chi}^0}}{2 \text{ TeV}} \right)^{2/3}. \quad (16)$$

Therefore, such cosmological scenario favors a gravitino mass at an intermediate scale above 10^7 GeV , and the gravitino mass in our model satisfies this bound clearly.

Furthermore, after $SU(2)_R \times U(1)_{B-L}$ gauge symmetry breaking, the leading tadpole term for S in Eq. (9) vanishes. Thus, to obtain the μ term which is forbidden by $U(1)_R$ symmetry, we need to generate the supersymmetry breaking soft term $A_\kappa^{S\Phi\Phi'} \kappa S\Phi\Phi'$. With it, we get the VEV of S as below

$$\langle S \rangle = \frac{A_\kappa^{S\Phi\Phi'}}{2\kappa}. \quad (17)$$

And then the μ term is given by

$$\mu = \frac{\lambda}{2\kappa} A_\kappa^{S\Phi\Phi'}. \quad (18)$$

For $\lambda = 2\kappa$, we have

$$\mu = A_\kappa^{S\Phi\Phi'}. \quad (19)$$

However, in no-scale supergravity, we have $A_\kappa^{S\Phi\Phi'} = 0$. To solve this problem, first, we consider M-theory on S^1/Z_2 [23]. For the standard Calabi-Yau compactification at the leading order or lowest order, we can realize no-scale supergravity [24], and there exists the next to leading order corrections [25, 26, 27]. In particular, we can have the non-zero supersymmetry breaking soft term $A_\kappa^{S\Phi\Phi'} \kappa S\Phi\Phi'$. To compare with no-scale supergravity, we consider moduli dominant supersymmetry breaking, whose the supersymmetry breaking soft terms for universal gaugino mass, scalar mass and trilinear soft term are [27]

$$M_{1/2} = \frac{x}{1+x} m_G, \quad (20)$$

$$M_0 = \frac{x}{3+x} m_G, \quad (21)$$

$$A = -\frac{3x}{3+x} m_G, \quad (22)$$

where $0 < x < 1$. For $x \sim 10^{-6} - 10^{-7}$, we can indeed have the TeV-scale supersymmetry breaking soft terms in the SSMS while gravitino mass is around 10^{9-10} GeV . Of course, there exists some fine-tuning for x .

Another way to generate the $A_\kappa^{S\Phi\Phi'} \kappa S\Phi\Phi'$ term is from the RGE running in no-scale supergravity [28, 29, 30, 31]. Because of $A = 0$ from the no-scale boundary condition, we can neglect the Yukawa contributions and the RGE for $A_\kappa^{S\Phi\Phi'}$ is

$$16\pi^2 \frac{dA_\kappa^{S\Phi\Phi'}}{dt} = -2 (g_{B-L}^2 M_{B-L} + 3g_{2R}^2 M_{2R}) \quad (23)$$

before the $SU(2)_R \times U(1)_{B-L}$ gauge symmetry breaking, and

$$16\pi^2 \frac{dA_\kappa^{S\Phi\Phi'}}{dt} = -4g_1^2 M_1 \quad (24)$$

after the $SU(2)_R \times U(1)_{B-L}$ gauge symmetry breaking. Here, $t = \ln\mu$, g_{B-L} , g_{2R} , and g_1 are respectively gauge couplings for $U(1)_{B-L}$, $SU(2)_R$, and $U(1)_Y$, and M_{B-L} , M_{2R} , and M_1 are the corresponding gaugino masses. The boundary condition for the gauge couplings at the $SU(2)_R \times U(1)_{B-L}$ gauge symmetry breaking scale is

$$\frac{1}{g_1^2} = \frac{1}{g_{B-L}^2} + \frac{1}{g_{2R}^2}. \quad (25)$$

Because we do not present a complete model here, let us consider the simple case. For no-scale supergravity, we should run the RGEs from the string scale, otherwise, light stau will be the LSP [28, 29, 30, 31]. Thus, we run the RGE from string scale to the scale around the masses of S , Φ , and Φ' . For $g_{B-L} = g_{2R} = 1$ and $M_{B-L} = M_{2R} = 2$ TeV, assuming the constant gauge couplings and gaugino masses, we get $\mu = A_\kappa^{S\Phi\Phi'} \simeq -700$ GeV for order one κ . Of course, in such kind of the left-right models, we generically need to introduce more particles, and the complete RGE study is much more complicated. Note that if we have more particles above the $SU(2)_R \times U(1)_{B-L}$ symmetry breaking scale, their gauge couplings will become larger at higher scale and then the magnitude of $A_\kappa^{S\Phi\Phi'}$ will be larger, which can give us larger μ term if we want. Therefore, we can indeed obtain the SSMs with TeV-scale supersymmetry and the intermediate-scale heavy gravitino.

In summary, to solve the problem in the μ -term hybrid inflation with canonical Kähler potential, we obtained the supersymmetry scenario which has the TeV-scale supersymmetric particles and intermediate-scale gravitino from anomaly mediation. Moreover, we for the first time proposed the μ -term hybrid inflation in no-scale supergravity where μ term is generated via the VEV of inflaton field after inflation. Considering four Scenarios for the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model, we showed that the correct scalar spectral index n_s can be obtained, while the tensor-to-scalar ratio r is predicted to be tiny, about $10^{-10} - 10^{-8}$. Also, the $SU(2)_R \times U(1)_{B-L}$ symmetry breaking scale is around 10^{14} GeV, and all the supersymmetric particles except gravitino are around TeV scale while gravitino mass is around 10^{9-10} GeV.

With the complete potential terms linear in S , we for the first time showed that the tadpole term, which is the key for such kind of inflationary models to be consistent with the observed scalar spectral index, vanishes after inflation or say gauge symmetry G breaking. Thus, to obtain the μ term, we need to generate the supersymmetry breaking soft term $A_\kappa^{S\Phi\Phi'}\kappa S\Phi\Phi'$, since we have $A_\kappa^{S\Phi\Phi'} = 0$ in no-scale supergravity. We showed that the supersymmetry breaking soft term $A_\kappa^{S\Phi\Phi'}\kappa S\Phi\Phi'$ can be realized properly in the M-theory inspired no-scale supergravity which has no-scale supergravity at the leading or lowest order. Also, we pointed out that the $A_\kappa^{S\Phi\Phi'}\kappa S\Phi\Phi'$ term with $A_\kappa^{S\Phi\Phi'}$ around a few hundred GeVs can be reproduced via the RGE running from string scale. Therefore, we proposed the no-scale μ -term hybrid inflation models where the sparticles in the SSMs are around TeV scale while gravitino is around 10^{9-10} GeV.

Acknowledgments

We would like to thank Qaisar Shafi very much for suggesting the project, and thank Qaisar Shafi and Nobuchika Okada very much for collaboration in the initial stage of the project and helpful discussions. This research was supported in part by the Natural Science Foundation of China under grant numbers 11135003, 11275246, and 11475238 (T.L.).

References

- [1] A. A. Starobinsky, “A New Type of Isotropic Cosmological Models Without Singularity,” Phys. Lett. B **91**, 99 (1980).
- [2] A. H. Guth, “The Inflationary Universe: A Possible Solution to the Horizon and Flatness Problems,” Phys. Rev. D **23**, 347 (1981).
- [3] A. D. Linde, “A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy and Primordial Monopole Problems,” Phys. Lett. B **108**, 389 (1982).
- [4] A. Albrecht and P. J. Steinhardt, “Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking,” Phys. Rev. Lett. **48**, 1220 (1982).
- [5] D. Z. Freedman, P. van Nieuwenhuizen and S. Ferrara, “Progress Toward a Theory of Supergravity,” Phys. Rev. D **13** (1976) 3214; S. Deser and B. Zumino, “Consistent Supergravity,” Phys. Lett. B **62** (1976) 335.

- [6] G. R. Dvali, Q. Shafi and R. K. Schaefer, “Large scale structure and supersymmetric inflation without fine tuning,” *Phys. Rev. Lett.* **73**, 1886 (1994) [hep-ph/9406319].
- [7] E. J. Copeland, A. R. Liddle, D. H. Lyth, E. D. Stewart and D. Wands, “False vacuum inflation with Einstein gravity,” *Phys. Rev. D* **49** (1994) 6410 [astro-ph/9401011].
- [8] J. C. Pati and A. Salam, “Lepton Number as the Fourth Color,” *Phys. Rev. D* **10**, 275 (1974) [*Phys. Rev. D* **11**, 703 (1975)].
- [9] M. U. Rehman, Q. Shafi and J. R. Wickman, “Supersymmetric Hybrid Inflation Redux,” *Phys. Lett. B* **683**, 191 (2010) [arXiv:0908.3896 [hep-ph]].
- [10] Q. Shafi and J. R. Wickman, “Observable Gravity Waves From Supersymmetric Hybrid Inflation,” *Phys. Lett. B* **696**, 438 (2011) [arXiv:1009.5340 [hep-ph]]; V. N. Senoguz and Q. Shafi, “Reheat temperature in supersymmetric hybrid inflation models,” *Phys. Rev. D* **71**, 043514 (2005) [hep-ph/0412102]; C. Pallis and Q. Shafi, “Update on Minimal Supersymmetric Hybrid Inflation in Light of PLANCK,” *Phys. Lett. B* **725**, 327 (2013) [arXiv:1304.5202 [hep-ph]]; W. Buchmüller, V. Domcke, K. Kamada and K. Schmitz, “Hybrid Inflation in the Complex Plane,” *JCAP* **1407**, 054 (2014) [arXiv:1404.1832 [hep-ph]].
- [11] G. Hinshaw *et al.* [WMAP Collaboration], “Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results,” *Astrophys. J. Suppl.* **208**, 19 (2013) [arXiv:1212.5226 [astro-ph.CO]].
- [12] P. A. R. Ade *et al.* [Planck Collaboration], “Planck 2015 results. XIII. Cosmological parameters,” arXiv:1502.01589 [astro-ph.CO]; P. A. R. Ade *et al.* [Planck Collaboration], “Planck 2015 results. XX. Constraints on inflation,” arXiv:1502.02114 [astro-ph.CO].
- [13] G. R. Dvali, G. Lazarides and Q. Shafi, “ μ problem and hybrid inflation in supersymmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$,” *Phys. Lett. B* **424**, 259 (1998) [hep-ph/9710314]; S. F. King and Q. Shafi, “Minimal supersymmetric $SU(4) \times SU(2)_L \times SU(2)_R$,” *Phys. Lett. B* **422**, 135 (1998) [hep-ph/9711288].
- [14] N. Okada and Q. Shafi, “ μ -Term Hybrid Inflation with Low Energy Consequences,” arXiv:1506.01410 [hep-ph].
- [15] M. Fukugita and T. Yanagida, “Baryogenesis Without Grand Unification,” *Phys. Lett. B* **174** (1986) 45.
- [16] For non-thermal leptogenesis, G. Lazarides and Q. Shafi, “Origin of matter in the inflationary cosmology,” *Phys. Lett. B* **258**, 305 (1991).

- [17] N. Arkani-Hamed and S. Dimopoulos, “Supersymmetric unification without low energy supersymmetry and signatures for fine-tuning at the LHC,” JHEP **0506**, 073 (2005) [hep-th/0405159]; G. F. Giudice and A. Romanino, “Split supersymmetry,” Nucl. Phys. B **699**, 65 (2004) [Nucl. Phys. B **706**, 487 (2005)] [hep-ph/0406088]; N. Arkani-Hamed, S. Dimopoulos, G. F. Giudice and A. Romanino, “Aspects of split supersymmetry,” Nucl. Phys. B **709**, 3 (2005) [hep-ph/0409232].
- [18] N. Haba and N. Okada, “Structure of split supersymmetry and simple models,” Prog. Theor. Phys. **114**, 1057 (2006) [hep-ph/0502213].
- [19] S. Antusch, M. Bastero-Gil, K. Dutta, S. F. King and P. M. Kostka, “Solving the eta-Problem in Hybrid Inflation with Heisenberg Symmetry and Stabilized Modulus,” JCAP **0901** (2009) 040 [arXiv:0808.2425 [hep-ph]].
- [20] S. Antusch, M. Bastero-Gil, J. P. Baumann, K. Dutta, S. F. King, and P. M. Kostka, “Gauge Non-Singlet Inflation in SUSY GUTs,” JHEP **1008** (2010) 100 [arXiv:1003.3233 [hep-ph]].
- [21] E. Cremmer, S. Ferrara, C. Kounnas and D. V. Nanopoulos, “Naturally Vanishing Cosmological Constant In N=1 Supergravity,” Phys. Lett. B **133**, 61 (1983); J. R. Ellis, A. B. Lahanas, D. V. Nanopoulos and K. Tamvakis, “No-Scale Supersymmetric Standard Model,” Phys. Lett. B **134**, 429 (1984); J. R. Ellis, C. Kounnas and D. V. Nanopoulos, “Phenomenological SU(1,1) Supergravity,” Nucl. Phys. B **241**, 406 (1984); “No Scale Supersymmetric Guts,” Nucl. Phys. B **247**, 373 (1984); A. B. Lahanas and D. V. Nanopoulos, “The Road to No Scale Supergravity,” Phys. Rept. **145**, 1 (1987).
- [22] B. Garbrecht, C. Pallis, and A. Pilaftsis, “Anatomy of F(D)-Term Hybrid Inflation,” JHEP **0612** (2006) 038 [hep-ph/0605264].
- [23] P. Horava and E. Witten, “Eleven-dimensional supergravity on a manifold with boundary,” Nucl. Phys. B **475**, 94 (1996) [hep-th/9603142].
- [24] T. Li, J. L. Lopez and D. V. Nanopoulos, “Compactifications of M theory and their phenomenological consequences,” Phys. Rev. D **56**, 2602 (1997) [hep-ph/9704247].
- [25] A. Lukas, B. A. Ovrut and D. Waldram, “On the four-dimensional effective action of strongly coupled heterotic string theory,” Nucl. Phys. B **532**, 43 (1998) [hep-th/9710208].
- [26] H. P. Nilles, M. Olechowski and M. Yamaguchi, “Supersymmetry breakdown at a hidden wall,” Nucl. Phys. B **530**, 43 (1998) [hep-th/9801030].

- [27] T. Li, “Soft terms in M theory,” Phys. Rev. D **59**, 107902 (1999) [hep-ph/9804243].
- [28] J. R. Ellis, D. V. Nanopoulos and K. A. Olive, “Lower limits on soft supersymmetry breaking scalar masses,” Phys. Lett. B **525**, 308 (2002) [hep-ph/0109288].
- [29] M. Schmaltz and W. Skiba, “Minimal gaugino mediation,” Phys. Rev. D **62**, 095005 (2000) [hep-ph/0001172].
- [30] J. Ellis, A. Mustafayev and K. A. Olive, “Resurrecting No-Scale Supergravity Phenomenology,” Eur. Phys. J. C **69**, 219 (2010) [arXiv:1004.5399 [hep-ph]].
- [31] T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, “The Golden Point of No-Scale and No-Parameter \mathcal{F} - $SU(5)$,” Phys. Rev. D **83**, 056015 (2011) [arXiv:1007.5100 [hep-ph]].
- [32] M. Y. Khlopov and A. D. Linde, “Is It Easy to Save the Gravitino?,” Phys. Lett. B **138** (1984) 265 ; J. R. Ellis, J. E. Kim and D. V. Nanopoulos, “Cosmological Gravitino Regeneration and Decay,” Phys. Lett. B **145** (1984) 181.